FROM FILAMENTS TO FABRIC PACKS – SIMULATING THE PERFORMANCE OF TEXTILE PROTECTION SYSTEMS

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ABSTRACT

Enhancements in lightweight and compliant textile based protection systems require the use of advanced materials as well as innovative reinforcement and hybridization schemes. To date, the majority of the ballistic textile development has relied on experiments and experience. While both analytical and computational methods for this class of materials, specifically fabrics and compliant composite laminates, has yielded insight, advanced material models and modeling capabilities with the resolution to accurately describe the interactions between the fibers, yarns and impacting projectile have only recently become available. Scientists at the U.S. Army Research Laboratory and the U.S. Army Research Office are collaborating with researchers in academia to develop and utilize advanced modeling capabilities for fabrics and armor grade composites used in body armor designs. The technology being developed will ultimately relate the constituent material – the filament – to its incorporation into a textile architecture through its manufacturing processes to a ballistic performance prediction of the corresponding textile and will allow a true materials-by-design approach to textile based protection systems. The current paper describes efforts associated with utilizing numerical analysis towards gaining a fundamental understanding of the projectile-textile interaction, the development of numerical techniques relating textile manufacture to ballistic prediction and hybridized systems currently being developed that can benefit from this detailed analysis.

1. INTRODUCTION

Compliant textile garments developed for protection have been produced for thousands of years - from the layers of linen utilized by the ancient Greeks through medieval Japan, where layers of silk were worn by samurai. The advent of high velocity firearms made protective textiles less effective, even with more recent commercial glass fibers and nylons, until the development of higher stiffness and strength filaments in the late 1960s. The aramid material, Kevlar, ushered in a new era of textile armor that continues to progress towards more mass efficient systems that offer the soldier exceptional protection. Yet as material advances continue, from improved aramids to high molecular weight polyethylenes (Dyneema, Spectra) and beyond (PBZ, M5), the development of textile armor systems that contain these advanced materials are driven primarily by experiments and experience. Although there have been a number of analytical models developed [Vinson and Zukas, 1975; Parga-Landa et al., 1995; Cunniff, 1999; Walker, 1999; Billon and Robinson, 2001; Phoenix, 2003] these models typically aren't used to design armor systems as they don't directly relate the structure of the as-manufactured textile to its corresponding ballistic performance. Rather, the models serve as a first level screening tool and provide insight into the relative importance of specific material parameters that influence performance. Although, how a ballistic textile is manufactured and its resulting configuration directly influences its behavior, details about its manufacture such as yarn denier, end count, etc., are much too detailed to be accurately accounted for in analytical techniques. Ballistic impacts into textile fabrics present a challenging modeling environment involving contact, complex stress and strain states with severe gradients, and friction between filaments and yarns. The sensitivity of ballistic performance to these and other mechanisms is not well understood. Highly detailed numerical simulations, however, can be developed that capture these complexities and provide insights into how the manufactured textile microstructure affects its performance. Ultimately, accurate simulations covering multiple-scales (from a filament-to-fabric level) will be required to understand how manufacturing effects relate

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to the interaction between the material and the projectile. The current effort will detail efforts that are accomplishing this and providing insight on the important mechanisms that affect performance.

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2. BACKGROUND

As textiles are comprised of many filaments, arranged in bundles (yarns), which are subsequently assembled in some repeating (or, in the case of nonwoven textiles - random) format, defining the continuum perspective at which to model the material will dictate the resolution of the results attained. If fabric is considered as a continuum, the details of the projectile interaction with the yarns (and, by default, the filaments) will not be attained. However, if fabric is considered a dense structure composed of individual yarns, and ultimately, fibers, the complexity of this definition makes analytical solutions to the problem intractable, but not numerical ones.

Numerous researchers have taken the former approach, whereby the fabric is defined to be the continuum and represented as: a homogenous, isotropic plate which deformed into a straight sided conical shell when impacted by a projectile, Vinson and Zukas, 1975, and Taylor and Vinson, 1990; a two dimensional isotropic membrane, Phoenix and Porwal, 2002, an anisotropic membrane, Simons and Shockey, 2001, with a constitutive behavior represented as a system of linear springs, Walker, 1999; or viscoelastic with rate dependent failure, Lim, Shim, and Ng, 2003. While all of these efforts report reasonable success when compared with experiment results, these approaches are inherently limited as they cannot account for important details such as yarn-yarn and projectile yarn interaction, which has been shown to influence the ballistic performance of the system, Briscoe and Motamedi, 1992 and Bhatnagar, 2006. However, recent efforts by Tabiei et al., King et al., 2005, and Boljen and Hiermaier, 2006, have developed multiscale formulations that endeavor to account for the microstructural aspects of a textile within a membrane formulation.

The latter approach was taken in the pioneering work of Roylance et al., 1973, who developed the simulation techniques that advanced the analysis from impact into an individual yarn to impact into a single ply of fabric. To accomplish this, these researchers represented the yarns of a fabric as a system of pin-jointed bars, depicted in Figure 1, and with this they were able to provide important insights into the behavior of a fabric as it was struck with a projectile. The technique allowed insight into the importance of material parameters, such as fiber modulus and failure strain, Roylance and Wang, 1981, and system effects such as fiber slippage and the detrimental effects of constraining the backsurface of multiple plies of fabric, Roylance et al., 1995. This technique was solved using the method of characteristics by Leech and Adeyafa, 1982, and has since been utilized and extended by a number of other researchers to include additional projectile geometries and edge conditions, Cunniff, 1992, nonlinear viscoelastic effects, Roylance and Wang, 1978, multiple plies, Ting et al., 1993, yarn crimp, Shim et al., 1995, and slip at the yarn crossover points, Ting et al., 1999. Yet, the representation of the textile with this approach does not truly represent the complex topology of an actual woven or braided fabric and as noted by Roylance, 1973, "the ballistic response of the textile structure depends on the response of the fiber with which it is woven as well as the structural geometry itself."

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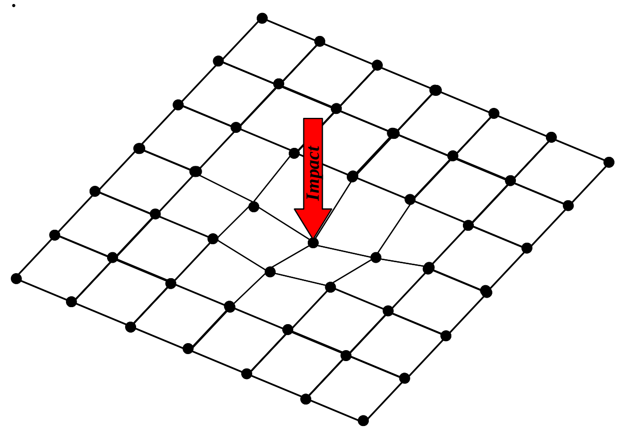


Fig. 1. Graphical representation of impact into a pin-jointed representation of a textile.

3. YARN LEVEL SIMULATIONS

As detailed above, numerical simulations of textile protection systems are not new, but the resolution that can be attained has been greatly enhanced as computational power has progressed. Cunniff, 1992, stated that at that time, the cost of performing numerical simulations of a 50 layers of fabric modeled at the detail of the yarn crossovers would be far in excess of building and testing the system. However, since this time, computational power has increased dramatically and numerical simulations of textiles comprised of discrete yarns and multiple layers has become possible. Shockey et al.1997, were among the first researchers to perform finite element simulations of impact into a fabric with each individual yarn represented with solid finite elements. These researchers analyzed the impact of a turbine fan blade, traveling approximately 80 m/s, on woven containment shrouds. Using this same level of resolution, Duan et al, 2005, 2006, investigated the impact of steel spheres and right circular cylinders of a single ply of Kevlar. Thorough studies of the influence of friction between

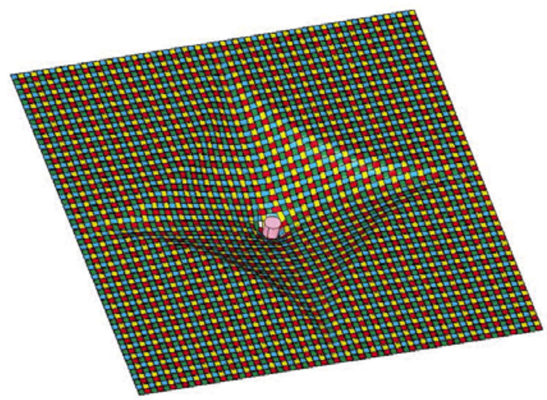
yarns and between the yarn and projectiles gave insight into the importance of friction in the projectile-textile interactions. Shown in Figure 2, a steel sphere impacts a 34x34 plain weave fabric having a) no friction between any of the interacting surfaces and b) having friction. The boundary conditions are 2 sides clamped, 2 sides free. In the case with no friction, it is seen that the steel sphere can wedge through the distended fabric. With friction, the projectile has to break more yarns before it can penetrate the fabric. In the simulations, friction, in general, does not act as a large energy dissipation mechanism. It is apparent that the friction allows more of the yarns to stay in contact with the projectile throughout the penetration event; thus allowing more energy to be lost as strain energy and kinetic energy in the yarn. The simulations allow the total energy to be partioned between strain energy, kinetic energy, and energy dissipated by friction. For the case with friction, 89% of the total kinetic energy the projectile lost was before yarn failure. 72% of the energy went into strain energy, while 7% was dissipated by friction, and the kinetic energy of the fabric accounted 10%. After the yarns started failing, the projectile lost an additional 11% of the energy, with the energy going into kinetic and frictional energy.

(a)

(b)

Fig. 2. Deformed mesh of a 34x34 Kevlar Fabric Layer impacted by a spherical projectile (a) without friction) and (b) with friction.

Additional insight has also been gained from the recent detailed simulations performed by Scott and Yen, 2006. In this study, individual yarns are modeled with multiple continuous membrane elements across the woven yarn's lateral surface. Note that the 8-node membrane elements provide much improved computational efficiency for the dynamic fabric analysis over the commonly used 3D brick elements. Figure 3 shows the deformed mesh of a layer of Kevlar® KM2 fabric subjected to normal impact of a steel cylindrical projectile at 249 m/sec. The frictional coupling and the density of cross-overs was studied and shown to influence the timing and extent of axial strains developed in the principally loaded yarns. Figure 4 shows a typical result that compares the strain distributions in a yarn for various friction coefficients. It shows that the peak yarn strain, which is directly related to yarn failure, is significantly increased as the friction coefficient reduced from 0.25 to 0. Real armor design variables include fabric construction and surface finish. It's quite possible that the performance of fabric based body armor or fabric reinforced composite armor could be improved following application of lessons learned from these ongoing computational studies.



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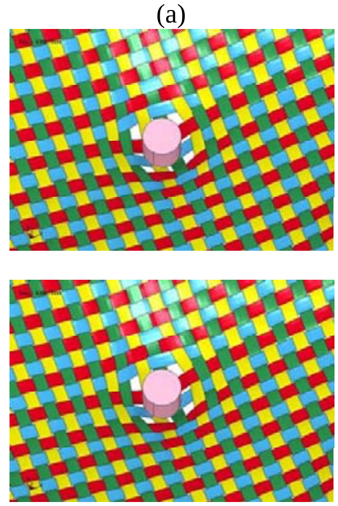
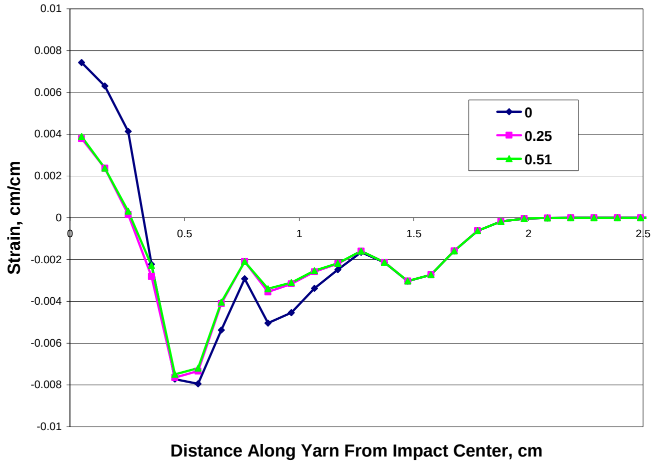


(b)

Fig. 3. (a) Deformed mesh of a 5x5 Kevlar fabric layer impacted by a cylindrical projectile and (b) close-up view of impacted area.



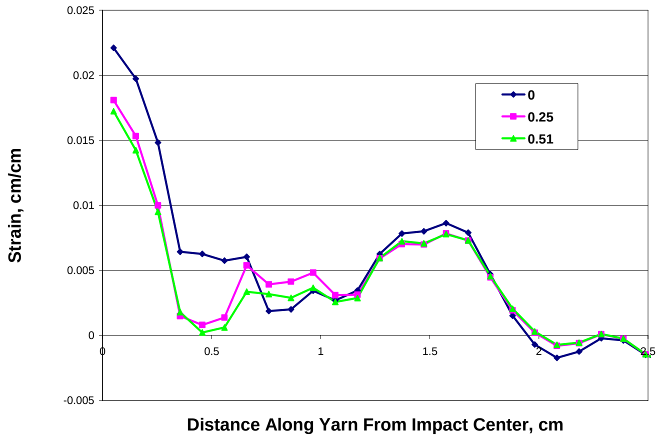


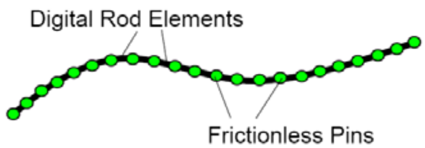
Figure 4. Strain distributions along impacted yarn for various friction coefficients at (top) 1.3 microseconds and (bottom) 2.8 microoseconds.

Although the development of these detailed finite meshes is labor intensive, this has not dissuaded a number of other researchers from advancing these detailed simulations and incorporating refinements such as multiple layers, Gu, 2004, Barauskas and Abraitiene, 2006, different weaves, Boljen and Hiermaier, 2006 and recently, efforts have been made by Zohdi and Powell, 2006, to model the fabric on the filamentary scale.

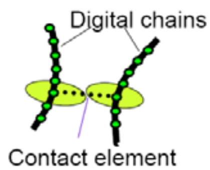
All of these yarn-level efforts start with the as-received textile product, where the geometry of the finite element mesh is developed from measurements and pictures of the textile cross-sections. For standard plain woven products, this is a readily feasible, albeit, time consuming process. However, some current optimized textile protective systems are not just utilizing layers of plain weave fabrics. As hybridized systems can become very complex (i.e. yarns can be comprised of more than one material, weaves can consist of yarns of different materials or deniers, and layers could be comprised of different materials or even different weaves or textiles). Ultimately, such optimized, hybridized systems cannot be readily simulated unless techniques are developed that can first simulate textile manufacturing processes and then the perform impact and penetration calculations. This capability is being developed and is described below.

4. DIGITAL ELEMENT ANALYSIS: SIMULATING TEXTILE MANUFACTURING AND PREDICTING BALLISTIC PERFORMANCE

The Digital Element Analysis (DEA) was initially developed by Wang and Sun, 2000, Sun and Wang, 2001, and Zhou, Sun and Wang, 2004 to simulate textile manufacturing processes. Depicted in Figure 5 are the three concepts that define the DEA approach to textile manufacturing simulations: namely, the digital chain, the contact of digital chains and yarn assembly. As depicted in Fig. 5(a), a digital chain is composed of many rod-elements, defined here as “digital elements”. Frictionless pins connect the rod elements. As the length of rod elements approaches zero, the digital chain becomes fully flexible and can be taken to be the physical representation of the fiber or filament. Fig. 5(b) illustrates the contact between two digital chains. When the element length approaches zero, contact between two digital chains can be represented by contact between nodes from two neighboring chains. If the distance between two nodes is smaller than the diameter of the digital chain, a contact element is added between them. The contact element can support both compressive and shear (friction) forces. In reality, a yarn is composed of many fibers and therefore, in the digital element approach, a yarn is modeled as an assembly of digital chains, as shown in Fig. 5(c). Once yarns are assembled from the digital chains, a global stiffness matrix can be determined and the fabric response to external loads can be derived in a procedure similar to finite element analysis. Textile manufacturing processes such as weaving, braiding, and three-dimensional weaving can be simulated and processing limitations, such as yarn jamming, can be determined, along with the corresponding microstructure and topology of the resultant textile. This can be extremely helpful with braided and three-dimensionally reinforced textiles, as the track of the yarns and filaments becomes extremely difficult to visualize (and therefore, difficult to mesh). Fig. 6(a) and (b) shows a 2D woven and 3-D braided fabric, respectively, generated using the digital element approach and Figure 7(a) and (b) show a comparison of the simulated cross sections with that of actual textiles. Excellent agreement is noted with both cases. With the digital element approach, the fiber-level micro-structure can be derived and both the yarn paths and cross-sectional shapes can be defined for most any textile manufacturing process, including multilayer weaves with three dimensional reinforcement. It should also be noted that hybridization on a filamentary and yarn level can be readily accomplished.



(a)



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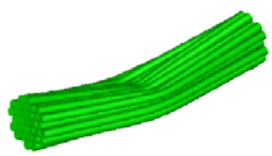
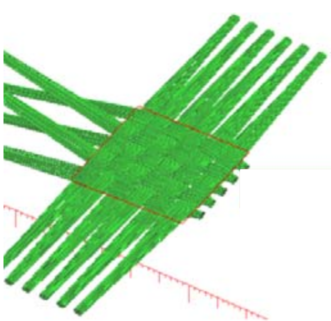


(c)

Fig. 5. (a) Digital chain is composed of many digital rod elements connected by frictionless pins; (b) contact between adjacent digital chains; (c) yarn can be represented as a multitude of digital chains, here 37 chains are utilized.



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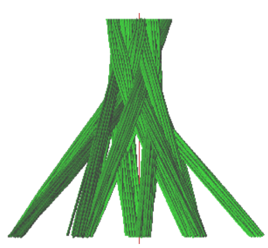
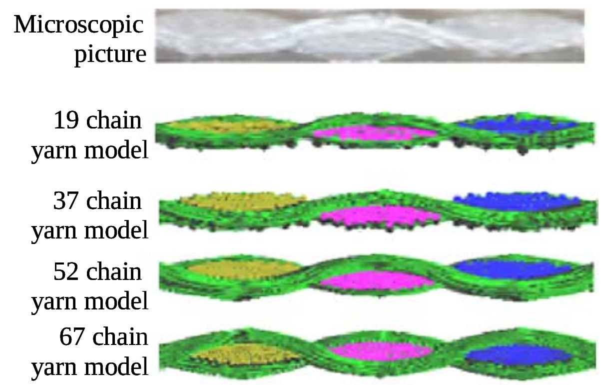


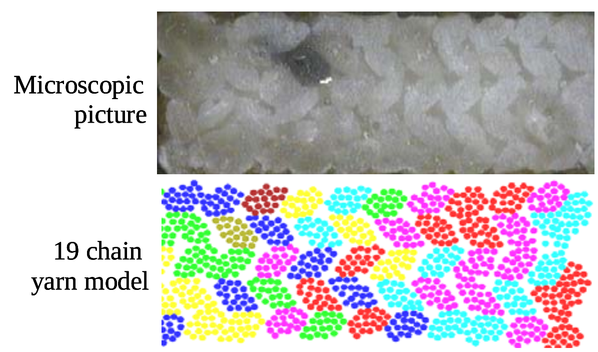
(b)

Fig. 6. (a) DEA simulation of weaving and (b) braiding.

Recently, Wang, Miao and Cheeseman, 2006, have extended the capabilities of the DEA to include an explicit formulation suitable to impact and penetration analysis. With this capability, the DEA can first simulate the manufacture of a textile and then simulate impact and penetration of the as-manufactured textile. Figure 8 shows a plain woven fabric generated using the DEA with yarns composed of five digital chains being impacted by a rigid sphere. The phenomenology of the impact and penetration is very similar to the analysis detailed above; however, the DEA can probe the complexities of the interactions occurring on a near filamentary level. Currently, the analysis is being validated with high resolution experimental data and is being extended to incorporate additional details of the filament including its shear failure, its stochastic strength and the strain rate dependency of both the strength and failure that has been observed in both aramids, Cheng, Chen and Weerasooriya, 2005, and high molecular weight polyethylenes, Huang, Wang and Xia, 2004. Further enhancements that are ongoing are the parallelization of the code to allow for very large scale computations.



(a)



(b)

Fig. 7. Comparison of cross-sections of DEA simulation and actual textile for (a) weaving and (b) braiding.

This numerical simulation tool, which directly links textile manufacturing from a near filament level to an end state ballistic prediction, will truly allow a 'materials by design' approach to textile protection systems, including the hybridization of yarns, weaves and layers, unusual textile architectures and tailored through thickness reinforcements.

5. HYBRIDIZATION AND NOVEL ENHANCEMENT

While the simulation technology is almost to the point of assisting in the design of these systems, the optimization of these systems is progressing. As mentioned above, the utilization of uniform layers of plain weave fabrics may not be the most mass efficient method of achieving ballistic performance. This can be seen in

the most recent generations of the Interceptor Outer Tactical Vest (OTV), which have been hybridized, Zheng, 2006. Hybridization can occur at the yarn level by incorporating dissimilar filaments into a yarn; at the fabric level, by weaving different materials and/or yarn deniers; at the ply level, by layering with different weaves, nonwovens and/or other materials. Hybridized systems of Kevlar and high molecular weight polyethylenes (HMPE) have been shown to have superior ballistic performance when compared to systems possessing the 100% Kevlar or 100% HMPE, Bhatnagar, 2006, and additionally, combinations of non-woven felts and other textile products have been shown to be advantageous over conventional textile materials for NIJ Level IIIA threats, Thomas, 2006.

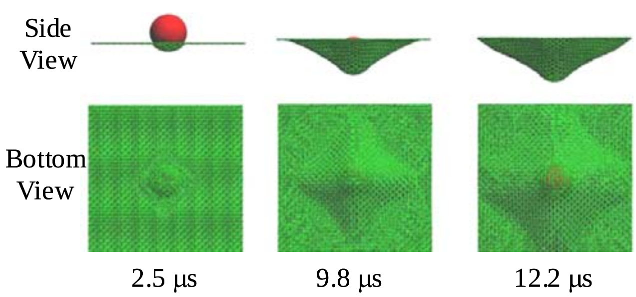


Fig. 8. DEA analysis of rigid sphere impacting a plain weave fabric. Note the fabric was created with the DEA with yarns comprised of five digital chains.

In other work being conducted by Tex Tech Industries and the University of Maine an array of different weave styles and non-woven felts are being combined along with a needling process to create a novel through thickness reinforced (3-D) hybrid ballistic fabric, Farrell and Erb 2006.

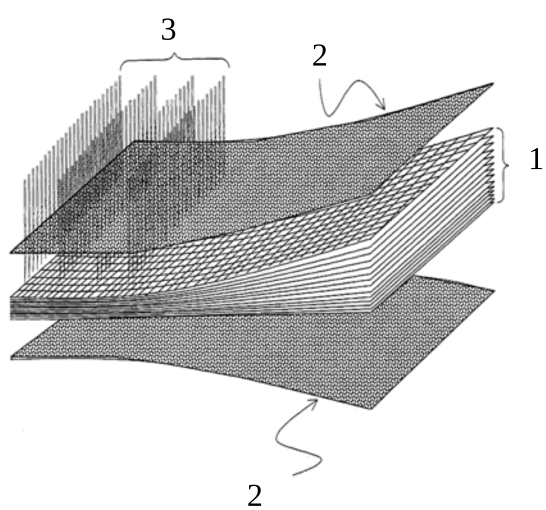


Fig. 9. Hybridization concept involving traditional weaves, felts and needling (furnished by TexTech Industries)

These fabric packs have shown promise in preliminary ballistic testing that produced V_{50} values between 9.5% and 13.4% higher for .22 FSP and 9mm projectiles, respectively, when compared to conventional 2-D fabric of the same denier. Many factors may be involved in the optimization of these 3-D hybrid materials. Factors such as the amount of needling, type of batt, and lay-up may prove to be extremely important. Research studying these concepts is ongoing but it is believed that the needling and felting inhibit the spreading of individual tows and increases the number of fibers that interact with the projectile. This 3-D hybrid material may provide a method to improve performance of textile based protective clothing using currently available fibers. If successful, body armor designs will be able to take advantage of a simplified manufacturing process because fewer layers of material will be involved in the counting procedure.

As the potential for performance improvements from hybridization are apparent, the textile design variables that could be investigated are numerous in addition to human factors such as comfort, flexibility, and heat dissipation. Maturing the simulation technology to assist in guiding these efforts is warranted and prudent.

6. CONCLUDING REMARKS

As computational power has increased, the detail that can be achieved in simulating the impact into textile protective systems has followed. Current efforts can reliably model yarn-level detail and provide insight into a number of mechanisms important to the penetration process. However, as hybridized systems and novel reinforcement schemes are being investigated, an even more refined multi-scale analysis is needed and is being developed. The DEA technique can simulate from a near filament level the manufacturing of a textile and then utilize the manufactured textile and simulate it subjected to the impact and penetration by a projectile. Methods such as DEA are becoming increasingly important for several reasons: (1) our military is facing an increased number of different threats that are rapidly adapted to counter our fielded protection systems and (2) nano-science is beginning to develop new fiber systems that may provide a substantial leap in our protection capabilities. These high resolution computational methods will enhance our capability for adapting to new threats and integrating new materials as they become available. They may help enable us to optimize the performance of our future protection systems at an accelerated pace as compared to today's development cycle. This capability is currently being developed and will allow a true materials-by-design approach to textile based protection systems.

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